JOURNAL OF PHYSICAL ORGANIC CHEMISTRY
J. Phys. Org. Chem. 2004; **17**: 957–966
DOI: 10.1002/poc.822

Review Commentary

Chemistry of protonated species in gaseous environments†

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Received 10 September 2003; revised 5 March 2004; accepted 6 March 2004

ABSTRACT: An overview is presented of gas-phase studies on the structure and reactivity of protonated species from the authors' research. Specific problems have been addressed operating in different gaseous environments, either in radiolytic systems at atmospheric pressure, enabling the NMR characterization of the neutral end products of gas phase ion–molecule reactions, or in low-pressure FT-ICR mass spectrometry, where ions can be trapped and characterized by their reactivity or spectroscopic features. Proton transfer reactions have revealed the role of competing acidic sites leading to biologically relevant $C_7H_7O^{\cdot}$ radical species and of competing basic sites in substituted benzenes. Proton transfer reactions have also been used as a tool to form elusive cations, e.g. c-$C_3H_7^+$, modulating the reaction energetics, and to unveil the structure and occurrence of degenerate isomerization processes within the benzenium ion.

KEYWORDS: proton transfer; ion–molecule reactions; H/D exchange; radical cations; $C_3H_7^+$ ions; gas-phase basicity; radiolysis; FT-ICR mass spectrometry

INTRODUCTION

The general category of protonated species includes positively charged species containing one (or more) mobile hydrogen atom. Gas-phase studies in the authors' recent research activity have been designed to chacterize these species both with regard to their structure and to their reactivity. The two issues are closely related though, because the structure of an ion may be inferred from its reactivity, for example from its dissociation dynamics or from the bimolecular reactivity, embracing the ensuing ionic product pattern and relative kinetic rate constants.[1–5] In favorable cases the characterization of the neutral end products of the ion–molecule reaction may be accomplished providing a complete view of the reaction pattern and circumstantial evidence on the ionic intermediates.[6,7] Since these ions are protonated species, the prominent reaction will be a proton tranfer reaction yielding the conjugate base of the ion, which can be investigated with regard to its structure, gas-phase basicity (*GB*) and protonation sites. Spectroscopic tools can also be used to characterize the structure of a gaseous ion.[8,9] By these means the possible occurrence of degenerate isomerization processes (for example, hydrogen migrations) or non-degenerate isomerizations involving skeletal rearrangement can be investigated. This report provides a concise account of recent issues that have been addressed by the authors as described in the cited references. Of course other investigators have contributed greatly to the progress in these fields and the original references should be consulted for a more comprehensive background.

Gaseous environments can range from a highly dilute gas phase, such as the very low pressure medium in the cell of an FT-ICR (Fourier transform ion cyclotron resonance)[10] spectrometer [ca 10^{-8} Torr (1 Torr = 133.3 Pa)] up to the atmospheric pressure typical of a radiolytic approach,[6,7] with a range of intermediate situations. These two extreme backgrounds imply different experimental approaches to the study of ion chemistry besides, most importantly, different physical conditions that will be experienced by the ion, for example, the ion lifetime, the frequency of unreactive collisions and the prevailing energy equilibration mechanism.

THE ACIDITY OF BENZYL ALCOHOL AND *p*-CRESOL RADICAL CATIONS

The problem of assessing the basicity and structure of the conjugate base of a protonated species is especially

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†Paper presented at the 9th European Symposium on Organic Reactivity, 12–17 July 2003, Oslo, Norway.

Contract/grant sponsor: Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR).

interesting when the neutral is not easily accessible. For example, a radical is obtained when the ion undergoing deprotonation is a radical cation. Radical cations are important reaction intermediates in chemistry and biochemistry and two isomeric radical cations have been examined because they serve as models of important biochemical intermediates. The gas-phase study of the bare radical cation is expected to provide insights into the neat reactivity behavior without the interference of any solvent or counterion. Also, the gas phase can resemble, in some respects (for example, with regard to the dielectric properties), the hydrophobic environment within the active site of an enzyme far better than an aqueous environment. Benzyl alcohol may be viewed as a building unit of lignin. The enzyme lignin peroxidase depolymerizes lignin and evidence has been presented that an electron transfer reaction takes place to form radical cations resembling benzyl alcohol radical cations.

It is known that alkylaromatic radical cations are strong α-carbon acids both in the gas phase and in solution. They react with bases to form products arising from α-carbon deprotonation.[11–16] In agreement with this general behavior 4-methoxybenzyl alcohol radical cations give rise to products that imply a deprotonation step. However, whereas in aqueous acid solutions, these species behave, as expected, as carbon acids, in the presence of OH^- they exhibit oxygen acidity, i.e. the key step in their decay seems to involve deprotonation at the alcoholic OH group.[17] With these premises, the gas-phase deprotonation of the radical cations derived from benzyl alcohol was studied by FT-ICR providing a clear picture of the reaction of interest in the absence of any further decay process.[18] In a typical experiment the radical cations ($AH^{+\cdot}$) were formed by EI at low electron energy in the external ion source. They were led into the ICR cell and thermalized by unreactive collisions with Ar, admitted via a pulsed valve. Their reactivity was then examined with respect to reference bases (B) of known basicity. In all cases proton transfer to the base is the only reaction observed [Eqn (1)].

$$AH^{+\cdot} + B \rightleftarrows [AHB]^{+\cdot} \rightarrow A^{\cdot} + BH^{+} \qquad (1)$$

The proton transfer reaction from the radical cation becomes increasingly fast as the base B is stronger, fulfilling the expectation that as the reaction becomes increasingly exoergonic, the bimolecular rate constant increases until the collisional limit is reached, when all the collision complexes evolve to products. Within this framework, the reaction efficiencies ($Eff = k_{\mathrm{exp}}/k_{\mathrm{coll}}$) for the proton transfer reactions from the selected radical cation to a set of reference bases (B) of known *GB* are fitted by a parametric function allowing the evaluation of the *GB* of the radical, the conjugate base of the radical cation [Eqn (2)].[19]

$$Eff = \frac{a}{1 + \exp\{b[-GB(\mathrm{B}) + c]\}} \qquad (2)$$

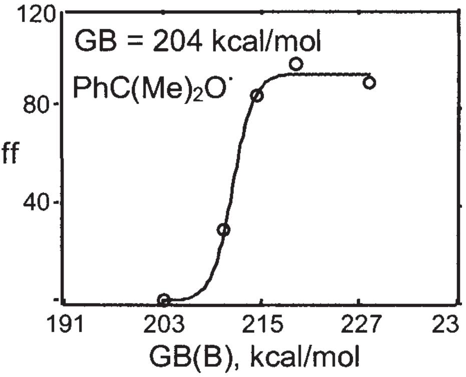


Figure 1. Plot of the efficiency (*Eff*) of the proton transfer reactions from $PhC(Me)_2OH^{+\cdot}$ to reference bases B versus *GB*(B).[18] The experimental values are fitted by the solid line according to Eqn (2)

At the same time the question arises as to which is the site of proton abstraction by the base. This problem may be approached in a stepwise fashion using methyl-substituted substrates that can only display either O- or α-C-acidity. The radical cation of cumyl alcohol can only undergo deprotonation at the hydroxyl group, whereas the radical cation of benzyl methyl ether can only react at the benzylic methylene group. Both radical cations undergo deprotonation, showing that both an α-C-hydrogen and a hydroxyl-hydrogen can be removed by the base. The curves obtained by fitting the kinetic data to the parametric function yield a *GB* value of 204 kcal mol^{-1} (1 kcal = 4.184 kJ) for $PhC(Me)_2O^{\cdot}$ (Fig. 1) and $GB = 203$ kcal mol^{-1} for $PhCH(OMe)^{\cdot}$ (Fig. 2) suggesting that the O-acidity is comparable on thermodynamic grounds to α-C-acidity.[18] It could be expected that in $PhCH_2OH^{+\cdot}$ both acidic sites come into play and the expectation is borne out by using labelled substrates. The reaction of the ring-labelled substrate $C_6D_5CH_2OH^{+\cdot}$ shows that the ring hydrogens are not involved in the deprotonation reaction. This finding is in

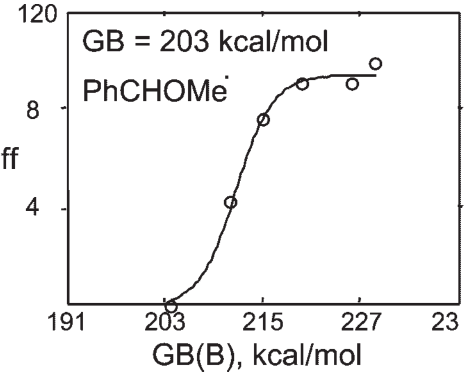


Figure 2. Plot of the efficiency (*Eff*) of the proton transfer reactions from $PhCH_2OMe^{+\cdot}$ to reference bases B versus *GB*(B).[18] The experimental values are fitted by the solid line according to Eqn (2)

line with the high proton affinity ($PA = 214\,\mathrm{kcal\,mol^{-1}}$) of the phenyl radical, which is distinctly higher than that, for example, of the benzyl radical ($PA = 200\,\mathrm{kcal\,mol^{-1}}$). In the reaction of $C_6D_5CD_2OH^{+\cdot}$ the reference base abstracts both D^+ and H^+ in a ratio that depends on its *GB* [Eqn (3)]. Thus, whereas D^+ transfer is by far predominant to cyclopropyl methyl ketone, the weakest among the bases used, H^+ transfer is favored by a factor of five in the case of 1,3-propanediamine. Other bases show a smooth increase of H^+ transfer as their *GB* increases (Fig. 3).[18]

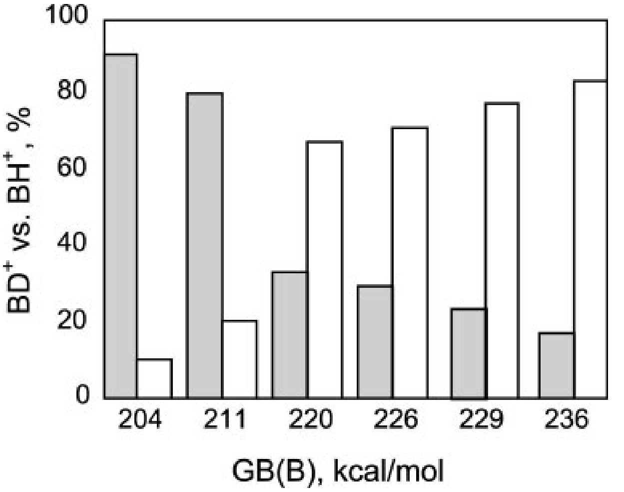


Figure 3. Branching ratio (%) between D^+-transfer (gray) and H^+-transfer (blank) from $C_6D_5CD_2OH^{+\cdot}$ to reference bases (B) of varying *GB*[18]

$$C_6D_5CD_2OH^{+\cdot} \xrightarrow{+B} \begin{cases} C_6D_5CDOH^{\cdot} + BD^{+} \\ C_6D_5CD_2O^{\cdot} + BH^{+} \end{cases} \qquad (3)$$

A rationale for this behavior has been sought through computations on the positive charge distribution in the radical cations of substituted benzyl alcohols, considering the possible effects on the reaction dynamics.[20]

p-Cresol, an isomer of benzyl alcohol, is a model of the group present in the amino acid tyrosine. This group is known to play a role in redox and radical processes that are usually thought to involve the formation of a phenoxyl radical. In the gas phase the *p*-cresol radical cation reacts through a proton transfer reaction with bases of increasing *GB* displaying a sharp onset towards the efficiency of 100% (Fig. 4).[21] The *GB* of the conjugate base obtained by the fitting to the parametric equation gives a value ($203\,\mathrm{kcal\,mol^{-1}}$), which is in reasonable agreement with a theoretical value for the O-centred radical ($201\,\mathrm{kcal\,mol^{-1}}$), whereas the *p*-hydroxybenzyl radical is predicted to be considerably more basic ($206\,\mathrm{kcal\,mol^{-1}}$).[22] In agreement with this expectation the reaction of labelled substrates shows that the hydroxyl hydrogen is in fact favored, although the selectivity decreases as B is more basic [Eqn (4)].

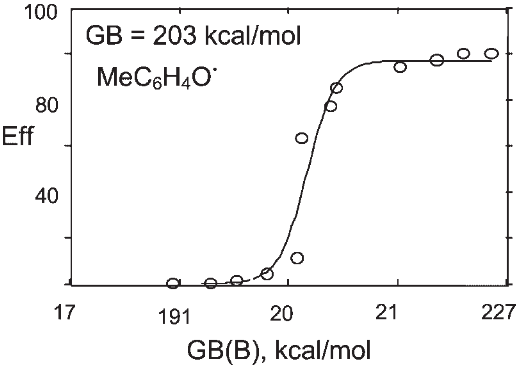


Figure 4. Plot of the efficiency (*Eff*) of the proton transfer reactions from *p*-$MeC_6H_4OH^{+\cdot}$ to reference bases B versus *GB*(B).[21] The experimental values are fitted by the solid line according to Eqn (2)

$$CD_3C_6D_4OH^{+\cdot} \xrightarrow{+B} \begin{cases} \xrightarrow{90\%} CD_3C_6D_4O^{\cdot} + BH^{+} \\ \xrightarrow{10\%} HOC_6D_4CD_2^{\cdot} + BD^{+} \end{cases} \qquad (4)$$

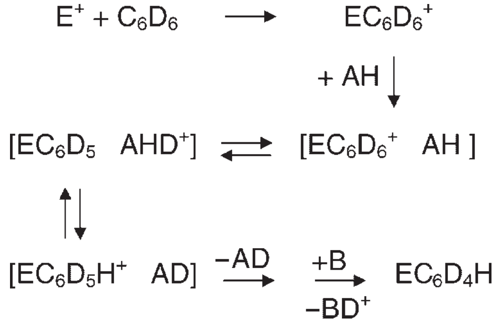
B = 1,3-propanediamine

It may thus be concluded that the competition between O-acidity and α-C-acidity is not peculiar just to benzyl alcohol radical cations. Moreover, in the tyrosine radical cation the possibility should be considered that the benzylic hydrogens may undergo attack by a base.

PROTONATION SITES IN SUBSTITUTED BENZENES

Proton transfer reactions could involve competing sites, as described in the previous section, for example. Similarly, the competition of different sites arises when a proton is delivered to a neutral base possessing two or more potential protonation sites. Simple aromatics such as monosubstituted benzenes provide an exemplary case. The involvement of competitive protonation sites has been assessed by studying the reactivity of the protonated species, the corresponding arenium ion, with regard to H–D exchange reagents.[23,24]

The problem has been approached by the radiolytic technique in an indirect way, generating an arenium ion and allowing it to undergo H/D exchange as outlined in Scheme 1. The reagent arenium ions $EC_6D_6{}^{+}$ are formed by 'E^+' attack on benzene-d_6, a procedure which can be extended to all charged electrophiles that are possibly formed by gas-phase radiolysis. In the framework of Scheme 1, collision of the reagents forms the ion–neutral complex, $[EC_6D_6^{+}\ AH]$. Within this complex a deuteron transfer event occurs. The D^+ transfer reaction can not



Scheme 1

lead to EC_6D_5 and AHD^+ as free product species, based on the relative *GB* of AH, typically lower than that of EC_6D_5. However, D^+ transfer is allowed to occur within the collision complex, taking advantage of the energy released in the electrostatic interaction of the reagent ion with the neutral. The key step involves the protonation of EC_6D_5, formed within the complex, by ADH^+ ions, finally leading to incorporation of an H atom on the *o*- *m*- and *p*-positions of the phenyl ring.

The H-distribution determined by ^{1}H-NMR analysis of the product arene shows that when E is an ethyl group the ^{1}H distribution favors the *ortho*/*para* positions (Fig. 5),[23] consistent with the higher basicity of these sites according to the site-specific proton affinities evaluated by theoretical calculations for the protonation of toluene.[25] In the presence of electron-withdrawing groups, such as CF_3, the ring H-incorporation is limited and is characterized by an *ortho*/*meta* distribution.[23] It is worth noting, that CF_3 (and other electron-withdrawing groups such as $COCF_3$ and NO_2) do not behave as simple *meta*-orienting groups towards electrophilic attack in the gas phase (Fig. 6).[23] Protonation at the *ortho*-position with respect to E appears to benefit from the interaction of the hydrogens on the tetrahedral carbon with the electronegative atoms on the substituent.[26]

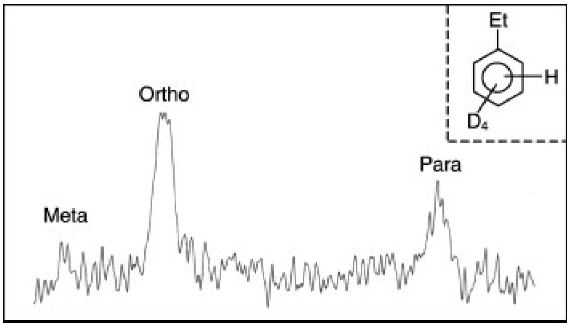


Figure 5. NMR spectrum of the aromatic protons of EtC_6D_4H obtained from the reaction of radiolytically formed Et^+ ions with C_6D_6 in the presence of H_2O as exchange reagent[23]

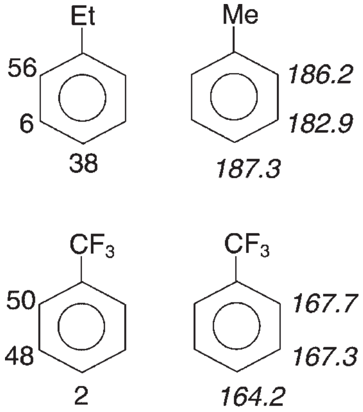


Figure 6. Experimental distribution of ^{1}H-incorporation[23] and site-specific PA values (in italics) as theoretically calculated for MeC_6H_5[25] and $CF_3C_6H_5$[26]

PROTONATED CYCLOPROPANE

Proton transfer reactions within an ion–neutral complex may also be designed to form and probe transient species. This methodology has been applied to the study of protonated cyclopropane (PCP). The protonation of cyclopropane is a route to $C_3H_7^+$ species. Three possible isomers have received major consideration in both experimental and theoretical studies, *i*-$C_3H_7^+$, *c*-$C_3H_7^+$ and *n*-$C_3H_7^+$.[27–32] The *i*-$C_3H_7^+$ cation is recognized as the most stable isomer and is the only isomer observable in solution.[33] *i*-$C_3H_7^+$ represents the simplest all-carbon and hydrogen carbenium ion to be prepared as a stable species in superacid media, where it was found to undergo scrambling of both hydrogen and carbon atoms. In this process the *n*-propyl cation and PCP are possibly involved as intermediate species. However, in spite of its important mechanistic role, PCP was never detected in solution. The protonation of cyclopropane by gaseous Brønsted acids of different acid strengths (AH^+) has been studied by the radiolytic approach at atmospheric pressure.[34] As the reagent ion becomes more acidic, that is the PA of the conjugate base is lower, the reaction is more exothermic and a greater amount of energy will be released in the product ion that is primarily formed [Eqn (5)]. This energy may be used to overcome the barriers to possible isomerization processes. Upon collision with the unreactive bath gas M, the ion will reach thermal equilibration with the environment.

$$AH^+ + c\text{-}C_3H_6 \xrightarrow{-A} [C_3H_7]^{+*} \xrightarrow{+M} [C_3H_7]^+ + M^* \quad (5)$$

The ionic species of interest, *c*-$C_3H_7^+$ and *i*-$C_3H_7^+$, have been trapped by reaction with benzene. Products of electrophilic aromatic substitution by the two ions are formed, *n*-C_3H_7—C_6H_5 and *i*-C_3H_7—C_6H_5, providing a probe of the relative amounts of *c*-$C_3H_7^+$ and *i*-$C_3H_7^+$, respectively, that are present in the ionic medium.[35] Their formation is ascribed to the sequence of steps characterizing the electrophilic aromatic substitution by gaseous cations [Eqn (6)].[36]

$$c\text{-}C_3H_7^+ + C_6H_6 \longrightarrow n\text{-}C_3H_7{-}C_6H_6^+ \xrightarrow[-BH^+]{+B} n\text{-}C_3H_7{-}C_6H_5 \qquad (6a)$$

$$i\text{-}C_3H_7^+ + C_6H_6 \longrightarrow i\text{-}C_3H_7{-}C_6H_6^+ \xrightarrow[-BH^+]{+B} i\text{-}C_3H_7{-}C_6H_5 \qquad (6b)$$

The effect of the exothermic nature of the protonation process when cyclopropane undergoes direct protonation by AH^+ is clear when the results obtained by using Brønsted acids of different acid strength are compared (Table 1).[34] The ensuing ions, $c\text{-}C_3H_7^+$ and $i\text{-}C_3H_7^+$ are found in different ratios, the abundance of $i\text{-}C_3H_7^+$ is rather high when the protonation is effected by powerful acids such as HCO^+ or H_3^+. On the other hand, when $C_2H_5^+$, a milder Brønsted acid, is the reagent ion only a minor fraction of $i\text{-}C_3H_7{—}C_6H_5$ is formed. These experiments thus suggest that the protonation by $C_2H_5^+$, which is exothermic by only 16 kcal mol^{-1}, may still be effective in yielding $i\text{-}C_3H_7^+$ ions, so that the activation barrier appears to be in the order of 16 kcal mol^{-1}.

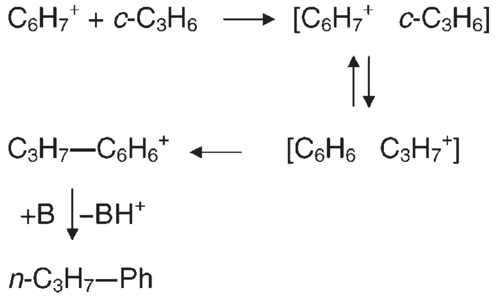
AH^+ can also react with benzene yielding protonated benzene. This species may be used as the active Brønsted acid performing a mediated protonation of cyclopropane. This reaction provides an alternative mechanism, predicting the formation of aromatic alkylation products from an ionic sequence of reactions initiated by the collision of a protonated aromatic compound with cyclopropane (Scheme 2).[37] The occurrence of this pathway is verified by the use of labelled reagents.

Notably, this mediated protonation pathway leads to the exclusive formation of $n\text{-}C_3H_7{—}C_6H_5$, suggesting $c\text{-}C_3H_7^+$ as the only ionic intermediate. This result may be explained both on the grounds of the nearly thermoneutral proton transfer between protonated benzene and cyclopropane and of the prompt nucleophilic trapping of the $c\text{-}C_3H_7^+$ ion by the same benzene molecule within the ion—neutral complex, a process estimated to occur in a time-scale of about 10^{-10} s.[38]

Table 1. Product pattern for the radiolytic alkylation of benzene by $C_3H_7^+$ ions formed by direct protonation of $c\text{-}C_3H_6$[34]

$AH^+ + c\text{-}C_3H_6 \longrightarrow A + [c\text{-}C_3H_7]^+$
$^*PA(c\text{-}C_3H_6) = 179\ \text{kcal mol}^{-1} \Delta H^\circ = PA(A) - 179\ \text{kcal mol}^{-1}$

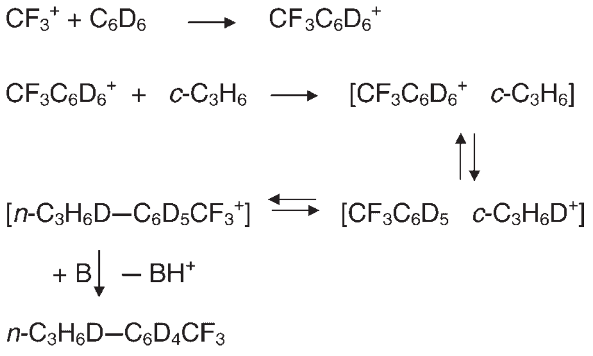
Reagent AH$^+$	PA(A)	Product (%)	
		$i\text{-}C_3H_7\text{-Ph}$	$n\text{-}C_3H_7\text{-Ph}$
$C_2H_5^+$	163	10	90
$CH_5^+/C_2H_5^+$	130/163	56	44
HCO^+	142	61	39
H_3^+	101	73	27



Scheme 2

Alternatively, ring-protonated α,α,α-trifluorotoluene can be used to initiate the reaction sequence. The isomer formed is still the n-propyl derivative in spite of an exothermicity of 11 kcal mol^{-1} for the proton transfer reaction. Furthermore, note that the reaction of the deuterated arenium ion, formed as shown in Scheme 3, implies a deuteron transfer to cyclopropane within the complex, ending with a D atom in the side-chain. The determination of the site of deuteration in the side-chain shows a statistical distribution of D in the n-propyl group of $n\text{-}C_3H_6D{—}C_6D_4CF_3$. This finding gives us an insight into the timing of events within the ion-neutral complex. In fact, it provides strong indication that fast equilibration of hydrogen atoms has occurred in the $c\text{-}C_3H_6D^+$ ion within the $[CF_3C_6D_5\ c\text{-}C_3H_6D^+]$ complex. At the same time it disproves an alternative possibility of concerted D^+-transfer and C—C bond formation, expected to lead to $CH_2DCH_2CH_2{—}C_6D_4CF_3$ as the only product.

The computed $C_3H_7^+$ isomers and their interconversion pathways are shown in Fig. 7 summarizing the results of recent calculations of representative species in the $C_3H_7^+$ potential energy surface.[34] The unsymmetrical corner-protonated cyclopropane is the most stable isomer retaining the three-membered ring. The activation energy for the isomerization to $i\text{-}C_3H_7^+$ is 13.1 kcal mol^{-1}, a value comparable to the experimental estimate of ca 16 kcal mol^{-1}. The investigated portion of the $C_3H_7^+$ potential energy surface shows that hydrogen scrambling



Scheme 3

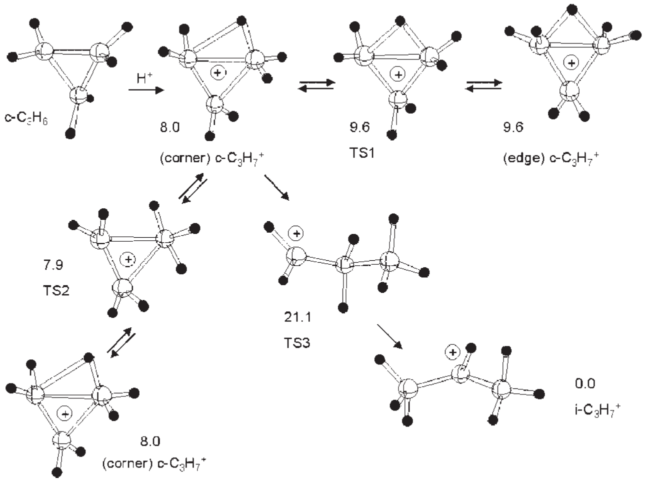
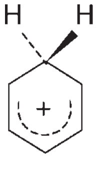


Figure 7. CCSD(T)/cc-pVDZ optimized geometries and relative CCSD(T)/cc-pVDZ//CCSD(T)/cc-pVDZ + ZPVE (MP2(full)/6–311G**) energies (kcal mol^{-1}) for c-C_3H_6 and representative $C_3H_7^+$ species[34]

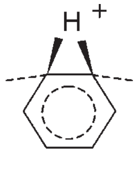
should be a fast process occurring via a 1,2-H shift by way of edge-protonated cyclopropane, accompanied by a barrierless methyl rotation in corner-protonated cyclopropane. The complete H-scrambling in protonated cyclopropane within the ion–neutral complex, [$CF_3C_6D_5$ c-$C_3H_6D^+$], is consistent with the fast rate expected for this process and speaks in favor of a discrete c-$C_3H_6D^+$ ion existing within the complex. The H randomization is bound to occur within the lifetime of such complexes estimated to be in the order of 10^{-10} s, in agreement, once again, with the low activation barrier predicted by the theoretical calculations.

STRUCTURE, REACTIVITY AND ABSORPTION FEATURES OF PROTONATED BENZENE

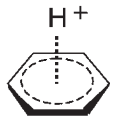
The prototypical arenium ion is the benzenium ion, $C_6H_7^+$, which can be obtained in the gas phase, just as in solution, from the protonation of benzene. The protonation of benzene in superacid solution is known to lead to a σ-complex (**I**), as observed by NMR spectrometry.[39] Structures that have been proposed for protonated benzene in the gas phase also include an edge-protonated π-complex (**II**) and a face protonated species (**III**).



I



II



III

It is generally agreed that the stable structure of protonated benzene is a σ-complex species, whereas the edge-protonated structure is a first-order saddle point 6–11 kcal mol^{-1} higher in energy and still higher, at ca 50 kcal mol^{-1}, a face-centred π-complex is a second-order saddle point.[40–45]

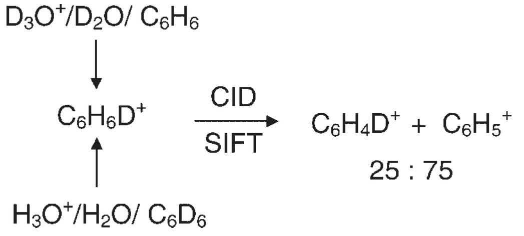
The experimental proton affinity of benzene, equal to 179 kcal mol^{-1}, is consistent with the value obtained by theory, thus proving **I** as the stable protonated benzene ion. The edge π-complex is a transition structure for the 1,2-H shift in the σ-complex. This process, first observed by dynamic NMR in superacid media, leads ultimately to the scrambling of the seven H atoms. The kinetic features of the process have been studied in gaseous benzenium and related arenium ions and found to be consistent with activation energies close to the computed value of 6–11 kcal mol^{-1}.[24,36] Finally, the face-centred π-complex has been invoked to account for the collision induced decomposition behavior of protonated benzene ions via H atom loss.[46]

The hydrogen scrambling process within benzenium ions has been studied with various mass spectrometric techniques, flowing afterglow-selected ion flow tube (FA-SIFT) and FT-ICR, and radiolysis. In the FA-SIFT technique ions are formed and allowed to react in a stream of He at 1 Torr, ensuring thermal equilibration with the surroundings. Benzenium ions of varying deuterium content have been formed by D^+ transfer from D_3O^+ to benzene, followed by further H–D exchange processes in the FA sector of the instrument.[47] Alternatively, ions of the same isotopic composition can be obtained by mirror experiments where $C_6(H,D)_7^+$ ions are formed by reaction of H_3O^+ with C_6D_6 followed by exchange with H_2O. Each mass selected ion was sampled in the SIFT sector by fast H^+–D^+ transfer to strong bases. The branching ratios for the competitive H^+ vs D^+ transfer to the same base (B) from a selected ion is found to be constant, irrespective of the formation pathway of the ion being assayed, as shown by the exemplary reaction of $C_6H_5D_2{}^+$ ions [Eqn (7)].

$$\begin{tikzcd} D_3O^+/D_2O/\ C_6H_6 \arrow[d] & \\ C_6H_5D_2{}^+ \arrow[r, "B", "SIFT"'] & BH^+ + BD^+ \\ H_3O^+/H_2O/\ C_6D_6 \arrow[u] & 76:24 \end{tikzcd} \qquad (7)$$

The invariance of the branching ratios to the mode of formation of the ions, i.e. protonation of C_6D_6 or deuteronation of C_6H_6, is consistent with the behavior expected for a population of $C_6(H,D)_7^+$ isotopomeric ions, where H–D equilibration is reached before sampling, namely within the ca 10^{-3} s time lapse required to reach the SIFT region. This evidence speaks against a stable non-interconverting face-protonated species.

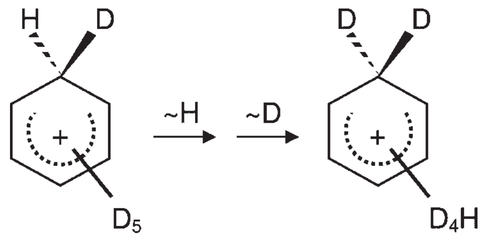
The structure of the same $C_6(H,D)_7^+$ ion population was independently probed by CID spectrometry of ions sampled in the SIFT sector.[47] The only significant fragmentation process leads to $C_6(H,D)_5^+$ ions, whose isotopic composition is the same from the two mirror experiments, as shown, for example, by the CID of $C_6H_6D^+$ ions [Eqn (8)].



(8)

This result is particularly relevant especially in the extreme cases of $C_6HD_6^+$ and $C_6H_6D^+$ ions. For example, within the $C_6DH_6^+$ ion population, the single D atom behaves in the same fashion whether it is derived from the primary D^+ transfer event from D_3O^+ to C_6H_6 or whether being the last D atom left in the sequence of events initiated by the H_3O^+ reaction with C_6D_6. Once again this result is in contrast with the hypothesis of a stable non-interconverting face-protonated species.

Alternatively, the unimolecular rearrangement of protonated benzene has been studied by gas-phase radiolysis, because this technique allows one to examine shorter time-scales than do conventional mass spectrometric techniques.[6,24] The superior time resolution allowed by the radiolytic technique has provided a closer, though only qualitative, estimate of the rate for the unimolecular automerization of benzenium ions in the gas phase. In this way it was found that at 120 °C H–D scrambling within the ion obtained by protonation of perdeuterated benzene is complete.[48] However, at 40 °C a significant fraction of $C_6D_6H^+$ ions retain the proton on the sp^3 carbon. Finally, kinetic evidence has shown that at −20 °C a major fraction of ions retain the primary structure. Since at 40 °C hydrogen shifts in benzenium ions occur in a time scale comparable to the deprotonation rate by an added base, the rate constant for H–D migration within benzenium ion is estimated to be in the order of 10^7–$10^8\ s^{-1}$ [Eqn (9)].



(9)

In conclusion, all the evidence based on reactivity behavior indicates that benzenium ions have a ground state σ-complex structure. They are prone to undergo hydrogen shift processes, which can be viewed as occurring via the edge-protonated structure, whose calculated energy relative to that of the σ-complex structure is in reasonable agreement with the rate of the process. No evidence has been found for a face protonated π-complex structure.

However, a direct spectroscopic characterization of $C_6H_7^+$ would be the most appropriate way to characterize this fundamental species and it appeared desirable in order to settle the gaseous benzenium ion problem. Recently it became possible to study the wavelength dependence of IR multiphoton dissociation (IRMPD) using the radiation from an infrared free electron laser (FEL) to activate the dissociation process. The experiments were performed in a collaboration with P. Maitre of the University of Paris, who developed this very interesting and powerful methodology and the experimental setup consisting of a mobile ICR ion trap coupled to the IR FEL.[49] It is possible to construct an IR spectrum by monitoring the amount of daughter ions produced as a function of the laser wavelength. Quantum chemical calculations are performed to characterize the IR absorption spectrum of the possible isomers of the ion of interest, which is then compared with the experimental IR spectrum derived from the wavelength dependence of the IRMPD process in order to identify the structure of the ion trapped in the ICR cell. The FEL IRMPD has been applied to $C_6H_7^+$ ions produced and stored in the ICR ion trap, which may undergo loss of H_2 as the lowest energy dissociation channel.[50] The barrierless dissociation to $H_2 + C_6H_5^+$ is reported to require 71 kcal mol^{-1},[42] meaning that the absorption of at least ten photons is needed to provide sufficient internal energy for $C_6H_7^+$ ions to undergo dissociation into $H_2 + C_6H_5^+$.

In Fig. 8 the relative intensity of the $C_6H_5^+$ product ions, providing an IR spectrum of the absorbing ion, is viewed together with the IR spectrum of the σ-complex

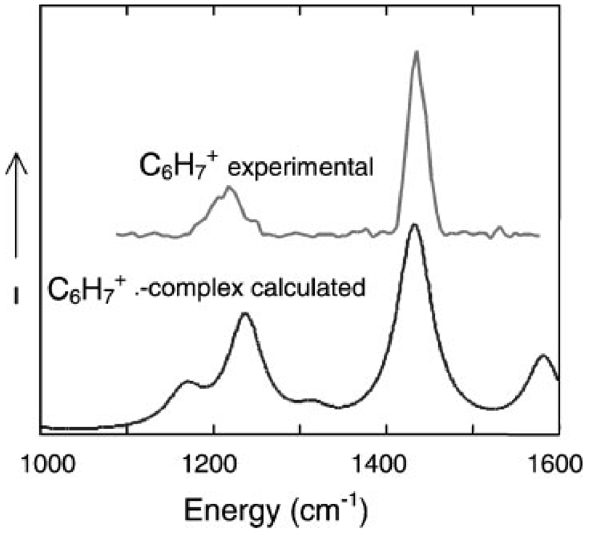
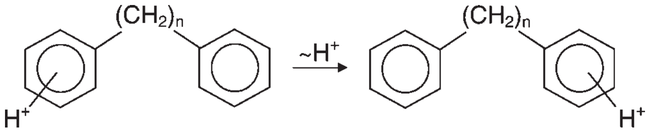


Figure 8. IRMPD spectrum of the $C_6H_7^+$ ion[50]

calculated using the B3LYP/6–311++G** method.[50] The two bands observed experimentally at 1228 and 1433 cm^{-1} match well with the two most intense absorptions determined theoretically at 1237 and 1434 cm^{-1} for the σ-complex. Protonated benzene is thus positively confirmed to be a σ-complex.

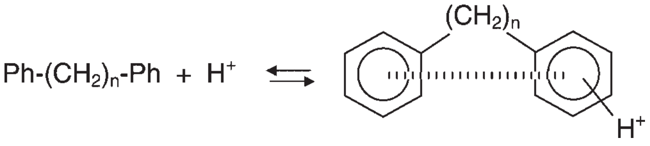
CATION–π INTERACTIONS IN ω-PHENYLALKYLARENIUM IONS

Gas phase studies can be designed to understand the role of solvent molecules and non-covalent interactions involving protonated species. We were interested in the microsolvation effect exerted by a remote phenyl ring on a positively charged center, for example, an arenium ion. The ionic intermediates of interest were formed by protonation or alkylation of α,ω-diphenylalkanes (DPAs).[24,51] In this way arenium ions are obtained that are covalently attached to a phenyl ring by a (poly)methylene chain. This group could approach the positively charged ring and provide electrostatic stabilization if the joining chain allows an appropriate conformation. Evidence has been obtained for the folding of the chain and the approach of the two rings by the study of both reactivity and thermodynamic features of these ions.[24,51] From the viewpoint of reactivity, interannular proton transfer processes have been observed.[22,51] Obviously, the proton can jump from one ring to the other if the two moieties are able to approach each other [Eqn (10)].



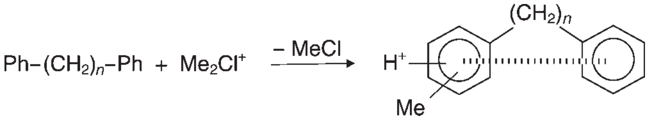
(10)

The *GB*s of DPAs are found to depend on *n*.[52] The structure dependence of the *GB*s for the DPA series with increasing number of methylene units shows that protonated 1,3-diphenylpropane is stabilized with respect to the close homologues, 1,2-diphenylethane and 1,4-diphenylbutane (Fig. 9). The unexpectedly high basicity of 1,3-diphenylpropane has been ascribed to the favorable conformation allowed to the protonated species where a parallel arrangement of the protonated and spectator ring can maximize the electrostatic stabilization of the positive charge. In protonated 1,3-diphenylpropane this conformation is compatible with an all-staggered conformation of the methylene chain [Eqn (11)].



(11)

The alkylation of DPAs studied by radiolytic and mass spectrometric techniques leads to the products of the electrophilic substitution reaction by way of arenium intermediates corresponding to the protonated alkylation products. In the methylation reaction the formation of the σ-complex was found to be the rate-determining step of the overall reaction on the basis of kinetic and mechanistic evidence.[53] For example, the dependence of the relative rates on *n* favors the $n = 3$ term. The trend is the same as the one found for the *GB*s of the same series of compounds, favoring 1,3-diphenylpropane over both 1,2-diphenylethane and 1,4-diphenylbutane (Fig. 10). The fact that the same trend is also displayed by the radiolytic reaction of Me_2Cl^+ is consistent with the proposition that the incipient formation of the methylated arenium ion should share features of the protonated species, approaching a σ-complex structure. Once again this feature can be explained by the peculiar stability of a sandwich-type conformation with a parallel arrangement of the arenium- and the spectator-ring allowed by the trimethylene chain [Eqn (12)].



(12)

The higher reactivity of 1,3-diphenylpropane with respect to the single ring reference substrate, toluene, is due to a lower activation energy by ca 8 kcal mol^{-1}. This

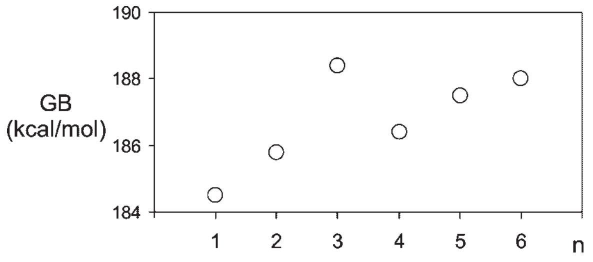


Figure 9. Gas-phase basicities of Ph—(CH$_2$)$_n$—Ph as a function of n[52]

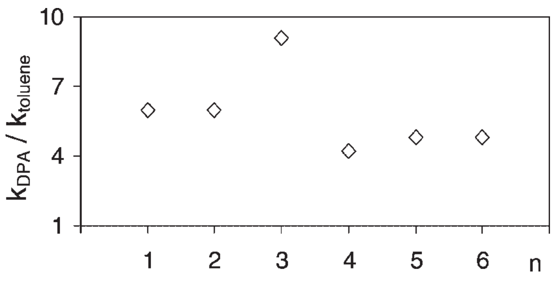


Figure 10. Normalized reactivities for the Me_2Cl^+ reaction with Ph—(CH$_2$)$_n$—Ph relative to toluene[53]

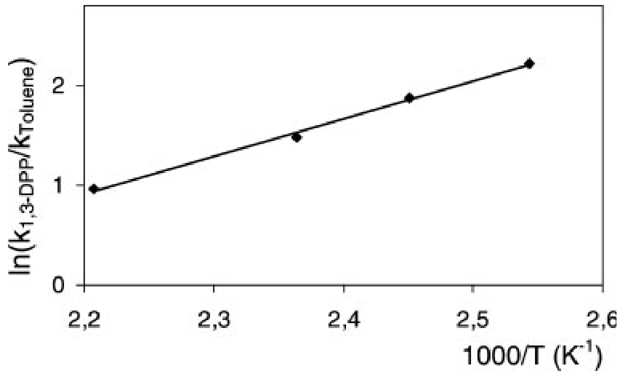


Figure 11. Arrhenius plot for the relative reactivity of Ph—$(CH_2)_3$—Ph towards Me_2Cl^+ with respect to toluene[53]

difference in the respective activation energies results from the Arrhenius plot shown in Fig. 11. It is interesting to note that this value is close to the binding energy of protonated benzene with neutral benzene forming an ion–neutral complex, $[C_6H_7^+ \; C_6H_6]$ that is the model for the arenium ion–phenyl ring interaction.[54] The matching of these energy quantities is strong evidence that the transition state for the methylation of 1,3-diphenylpropane gains substantial stabilization from the interaction of the spectator ring with the incipient arenium ion, whose formation is probably fairly advanced at this stage.

CONCLUSIONS

The gas-phase chemistry of protonated species provides valuable information on several of their structural and dynamic features. Exemplary issues that have been presented include the assessment of the structure of species of fundamental importance, the occurrence of degenerate isomerization processes, and, finally, the occurrence of cation–electron donor interactions, reminding us that gaseous ions, lacking any interactions with solvent molecules or counterions, exhibit the foremost request for electrostatic stabilization, exploiting any available source to this purpose. Positively charged sites conceivably face a similar quest within the hydrophobic environment at the active site of large biomolecules. The different gaseous environments control the physical conditions that the ions could experience, in addition to allowing different experimental approaches to the study of their chemistry.

EXPERIMENTAL

Depending on the specific problem, various experimental techniques have been exploited ranging from the ^{1}H-NMR characterization of neutral end products to the use of flow-sector instrumentation,[55] such as the FA-SIFT apparatus built at the University of Colorado, Boulder.[56] However, the routine methodologies used by the authors are FT-ICR[10] and a radiolytic approach.[6] FT-ICR experiments were performed with a Bruker Spectrospin FT-ICR mass spectrometer equipped with a cylindrical ‘infinity’ cell within a 4.7 T superconducting magnet and an external EI/CI ion source. The radiolytic experiments are based on the preparation of appropriate gaseous mixtures in glass vessels that are submitted to ionization by high energy radiation using a 220 Gammacell (Nuclear Canada Ltd.) up to total doses of ca 2×10^{-4} Gy. The radiolytic neutral products of ion–molecule reaction sequences are recovered and analyzed. The details of both types of experiments are amply described in the original papers reporting on the various topics of this review.

Acknowledgement

The authors are deeply indebted to their mentor, the late Professor Fulvio Cacace, for his inspiring guidance. Financial support from the Italian Ministero dell’Istruzione, dell’Università e della Ricerca is gratefully acknowledged.

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